Methodology for Composite Durability Assessment

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Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Contents

Objectives

AIM-C : Accelerated Insertion of Materials – Composites

(Funded by DARPA and managed by NavAir)

The goal of the AIM-C program

(1) Accelerate the insertion of new materials and processes

(2) Evaluate the effects of material, processing, and design on the performance of composite structures

Our objective is to analyze

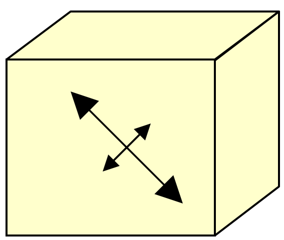
- **Environmental effects** (temperature, moisture)
- **Durability** (creep and fatigue life, residual strength)

State of the Art in Composite Analysis

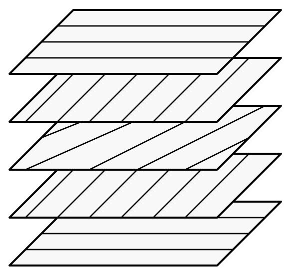
No principal stresses or strains

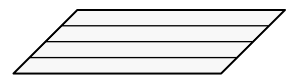
- Composites are highly orthotropic and viscoelastic

Involves numerous parameters



isotropic materials





Ply failure

Laminate failure

$E_x, E_y, E_z, G_{xy}, G_{xz}, G_{yz}$

$\sigma_x, \sigma_y, \sigma_z, \tau_{xy}, \tau_{xz}, \tau_{yz}$

X, X', Y, Y', S

Composite materials

Smallest level of imperfection is at the fiber / matrix level

Infinite combinations of parameters must be tested

Contents

Analytical Models

Strain Invariant Failure Theory (SIFT)

- Predicts initial and final failure of composite structures

Micromechanics

- Predicts 3-D ply properties and strain magnification factors

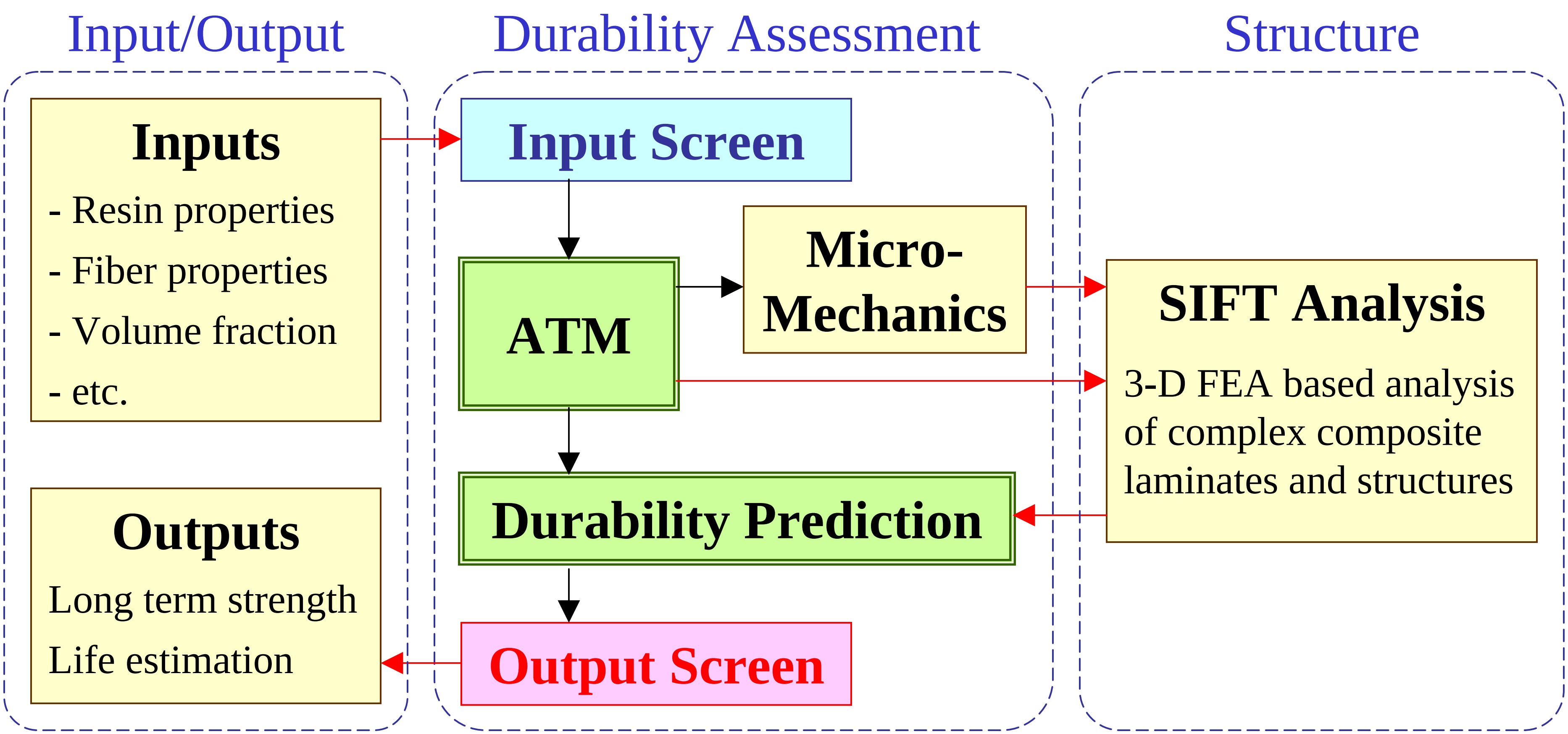
Accelerated Testing Methodology (ATM)

- Rapid generation of durability database as master curves

Linear Cumulative Damage Law (LCD)

- Life estimation under combined fatigue/creep loads
- Residual strength prediction

Analysis Architecture

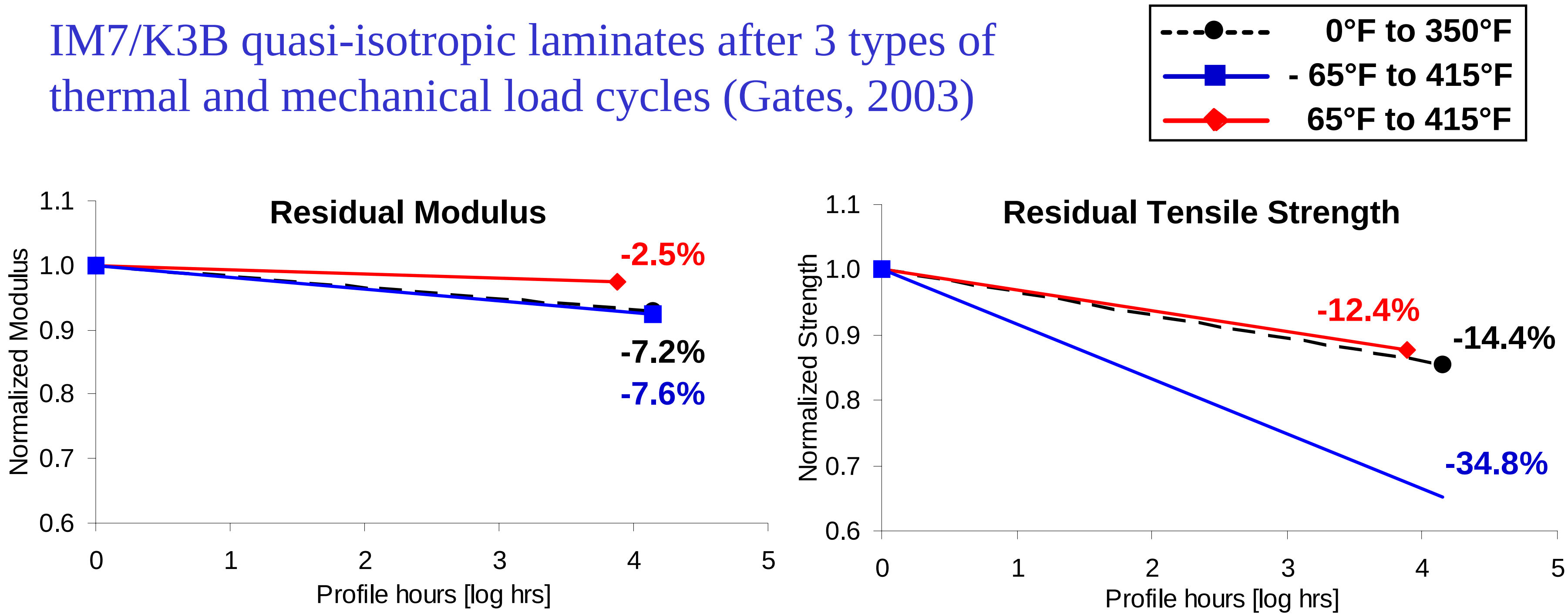


Verification Process

Evaluation of NASA HSR Data

- Mainly residual modulus and strength after thermal and mechanical load cycles
- IM7/5250-4 and IM7/K3B

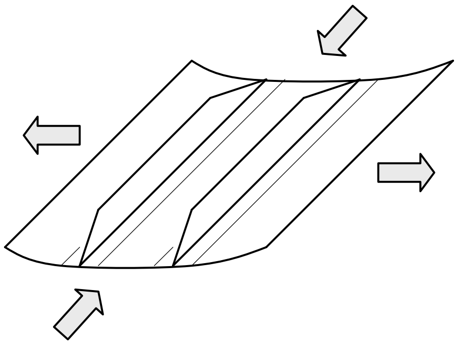
IM7/K3B quasi-isotropic laminates after 3 types of thermal and mechanical load cycles (Gates, 2003)

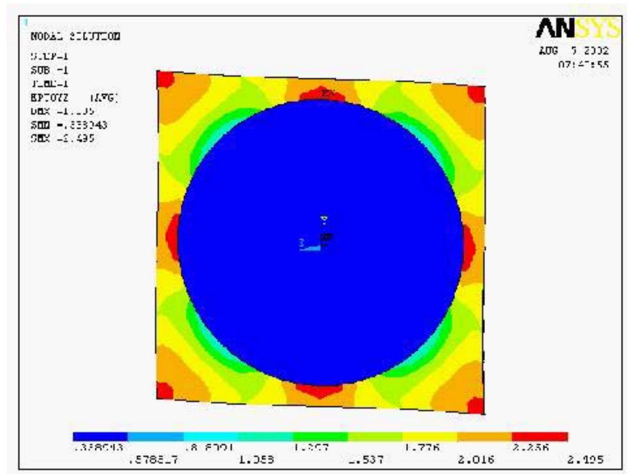


Use for the verification of the durability assessment methodology

Contents

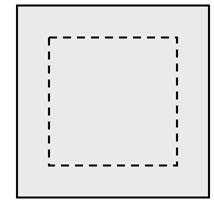
Strain Invariant Failure Theory (SIFT)





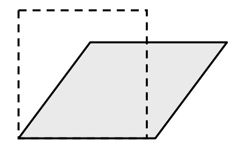
dilatational

$J_1=\varepsilon_1+\varepsilon_2+\varepsilon_3$



distortional

$$\varepsilon_{vM}=[\{(\varepsilon_2-\varepsilon_3)^2+(\varepsilon_1-\varepsilon_3)^2+(\varepsilon_1-\varepsilon_2)^2\}/2]^{1/2}$$



3-D macro strains
due to mechanical
and thermal loads

3-D micro strains
at various locations
in the fiber and resin
+
Micro thermal strains
due to CTE mismatch
of fiber and resin

Strain invariants
in the resin
and in the fiber

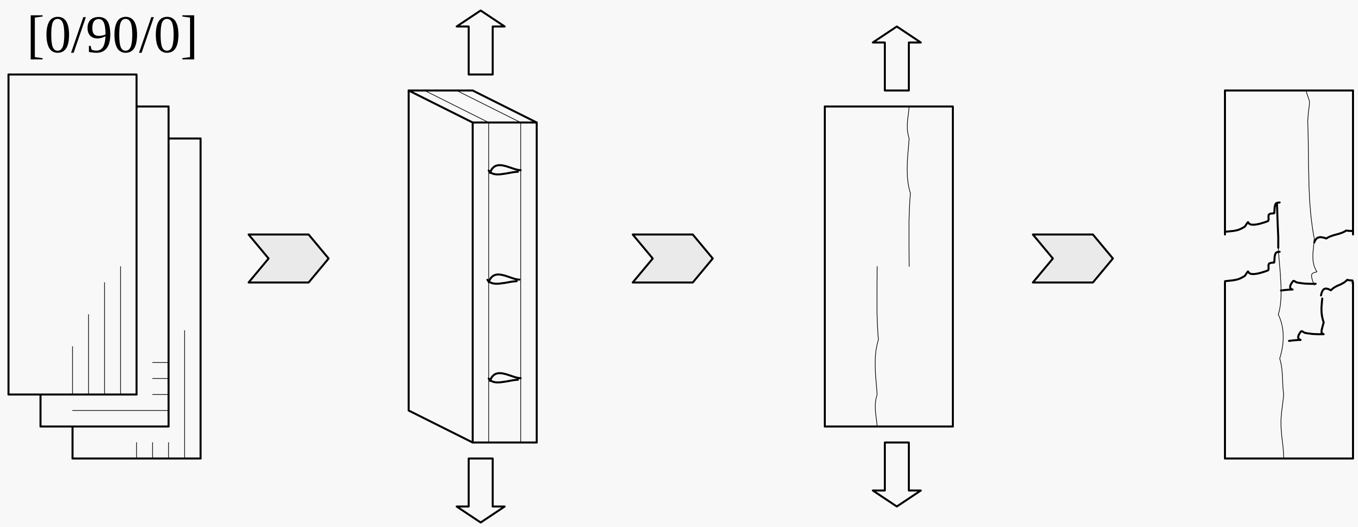
compare

Critical invariants

Final Failure Prediction Using MER

Maximum Energy Retention (MER) monitors retained and dispersed strain energies during the progressive damage to predict the final failure (2002, Gosse)

Schematic of MER used in the Stanford software



Intact state	90° J_1 failure	0° J_1 failure	0° e^f_{vM} failure
Dispersed Energy	90° $\sigma_2\varepsilon_2$	0° $\sigma_2\varepsilon_2$	0° $\sigma_1\varepsilon_1$
Stiffness	Assume $E_{eff} = E_{intact}(1 - 0.5U_{dispersed}/U_{intact})$		

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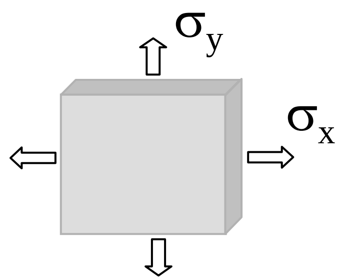
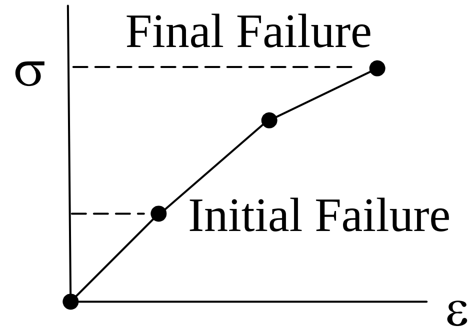
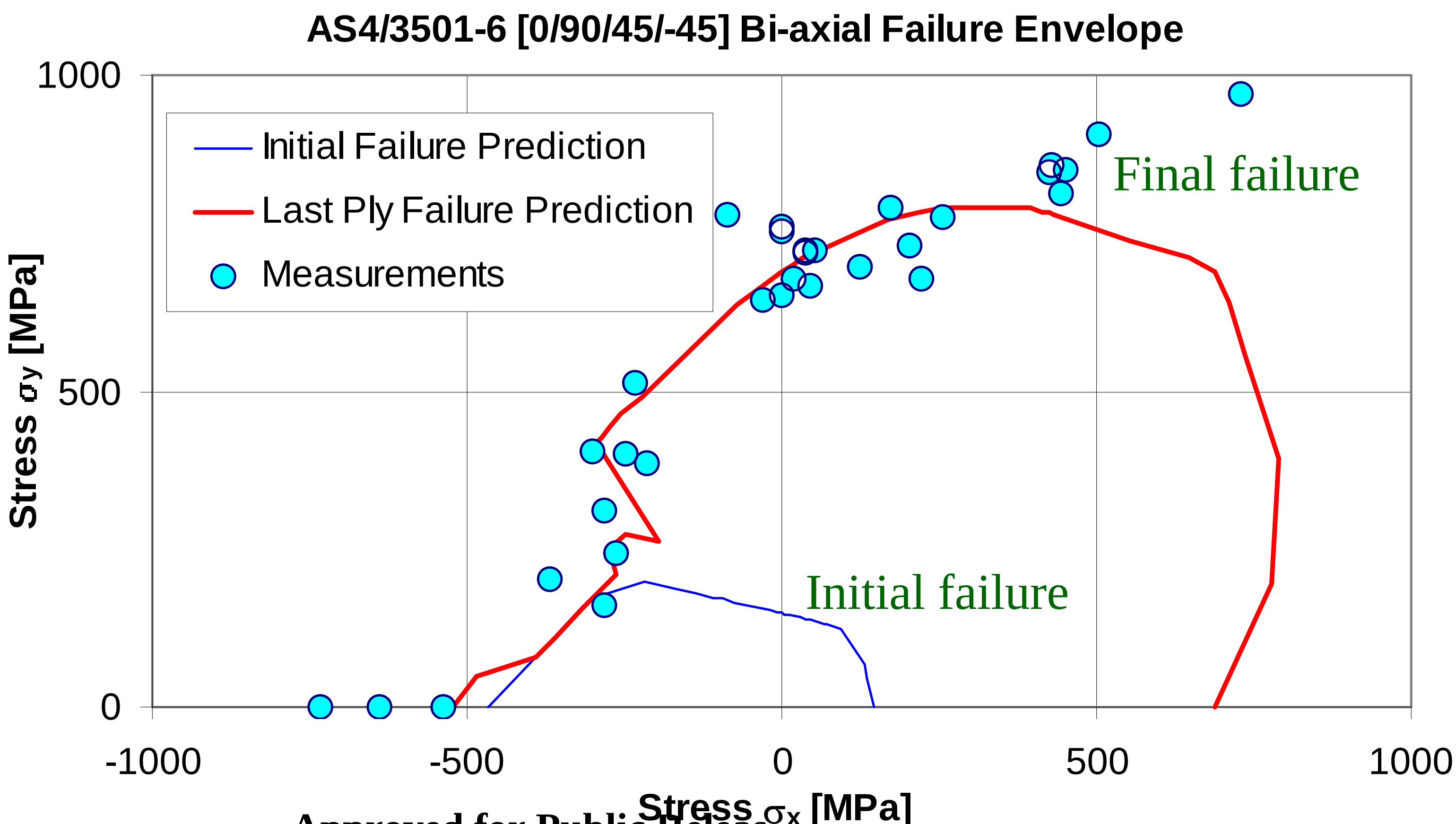
Examples of Failure Envelopes







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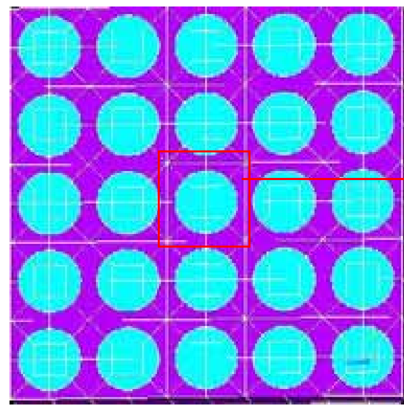
Contents

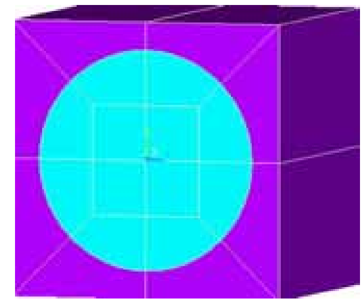
Micromechanics Finite Element Models

Cross-sectional view of continuous fiber composites

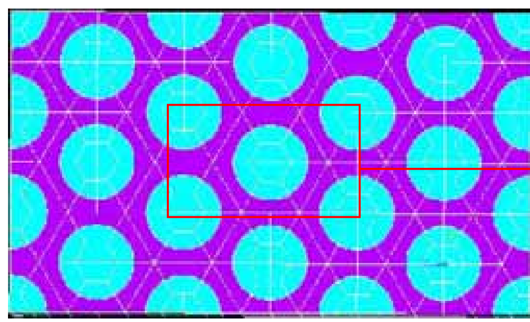
Square Array Model

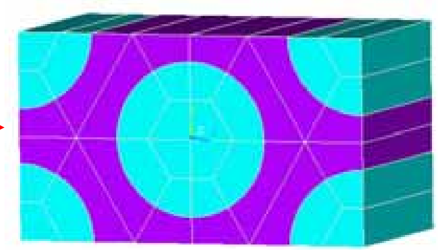


Unit Cells



Hexagonal Array Model

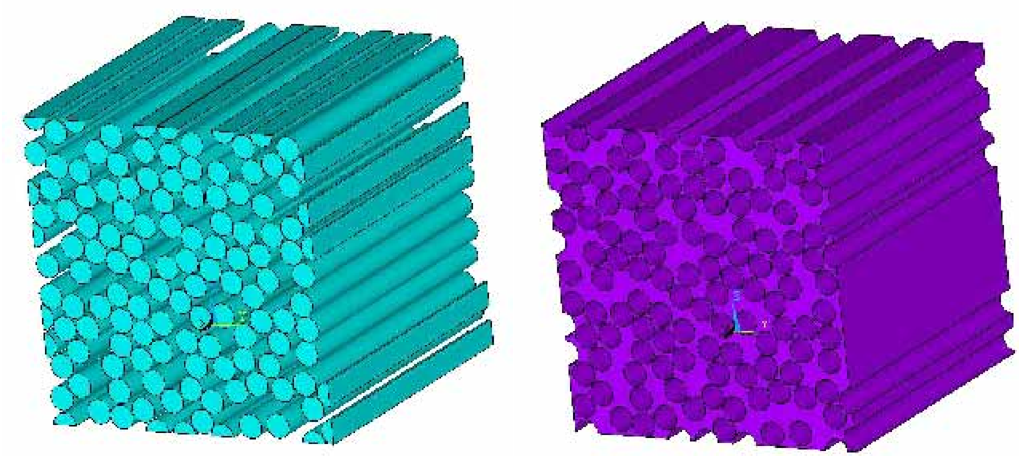




Predicts 3-D ply properties and strain magnification factors as functions of V_f, E_f, and E_m.

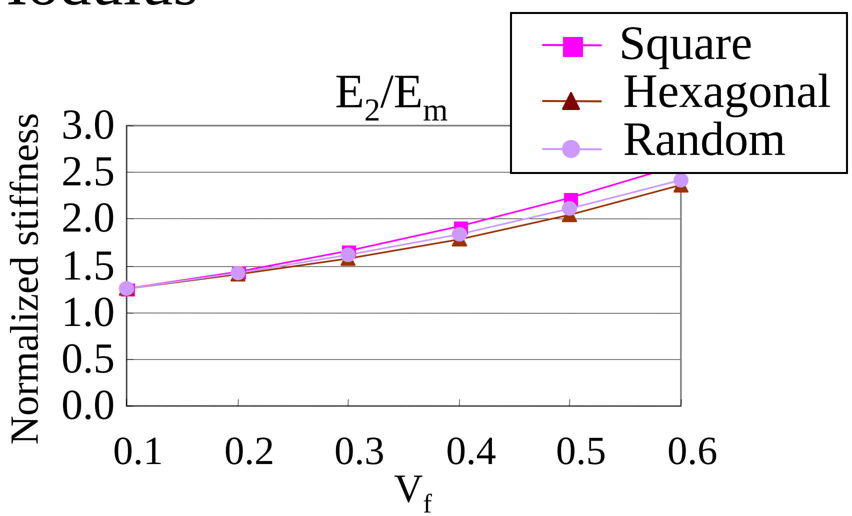
Evaluation of Random Fiber Array

Finite element model (Ha, 2003)



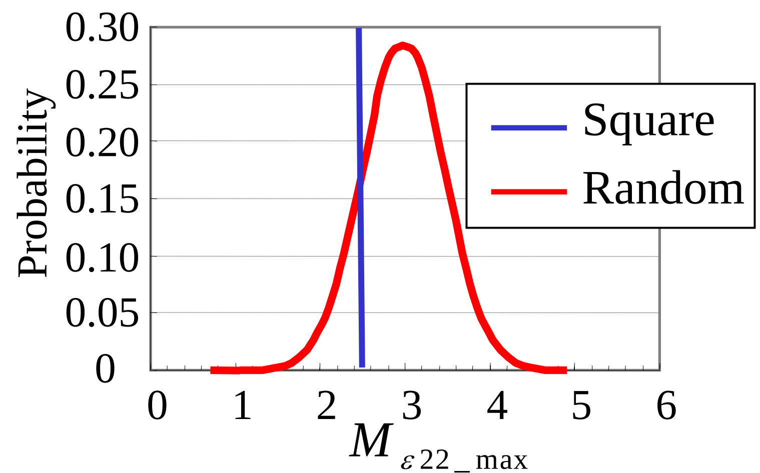
* $V_f = 0.60$
* Number of fibers = 120

Modulus



Identical to idealized array

Magnification



Distribution of microscopic failures

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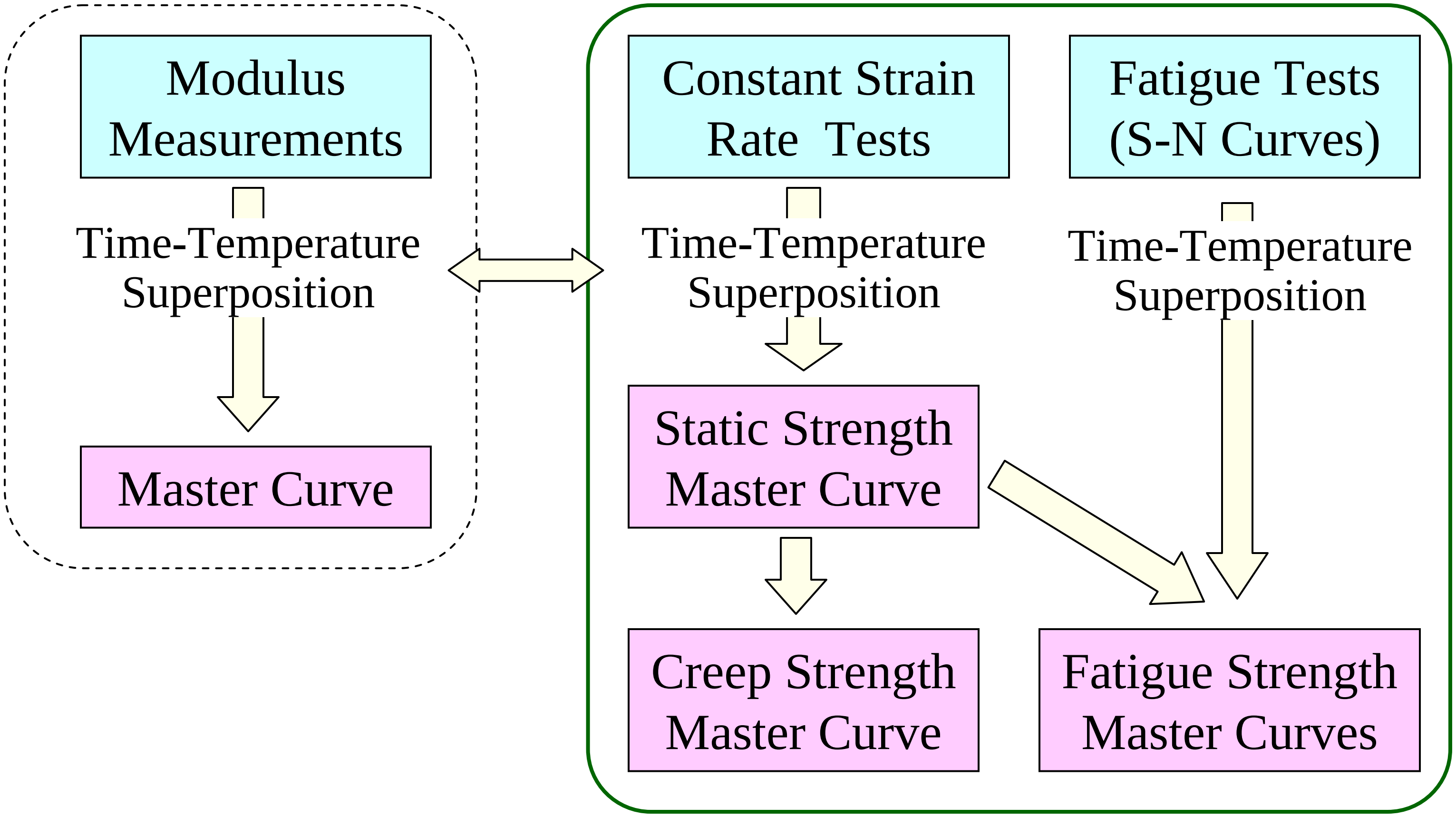
Contents

Accelerated Testing Methodology

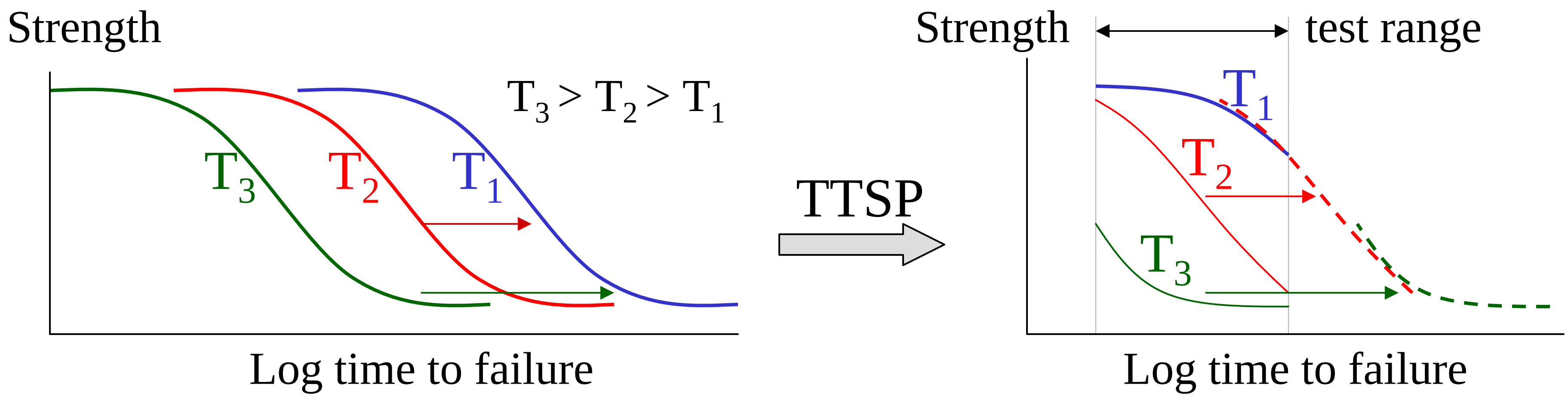
Series of tests at elevated temperature



Predictions for wide ranges of temperature and time to failure

Time-Temperature Superposition (TTSP)

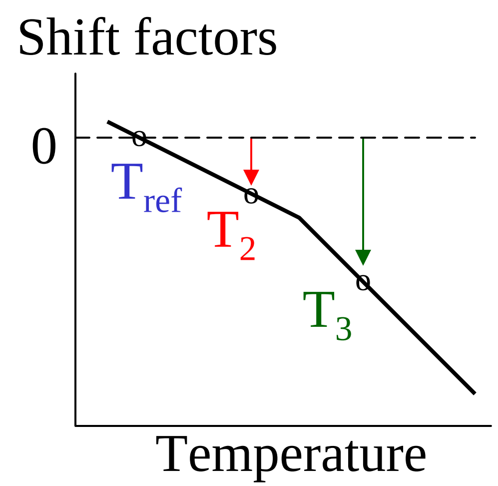
Assumption: Same shape for any temperature = Master Curve



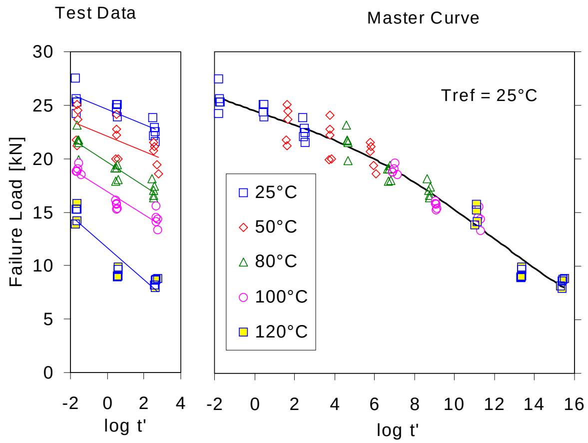
Curves can be superposed by horizontal shifts

⇒ Master curve can be generated from the fragments of curves at different temperatures

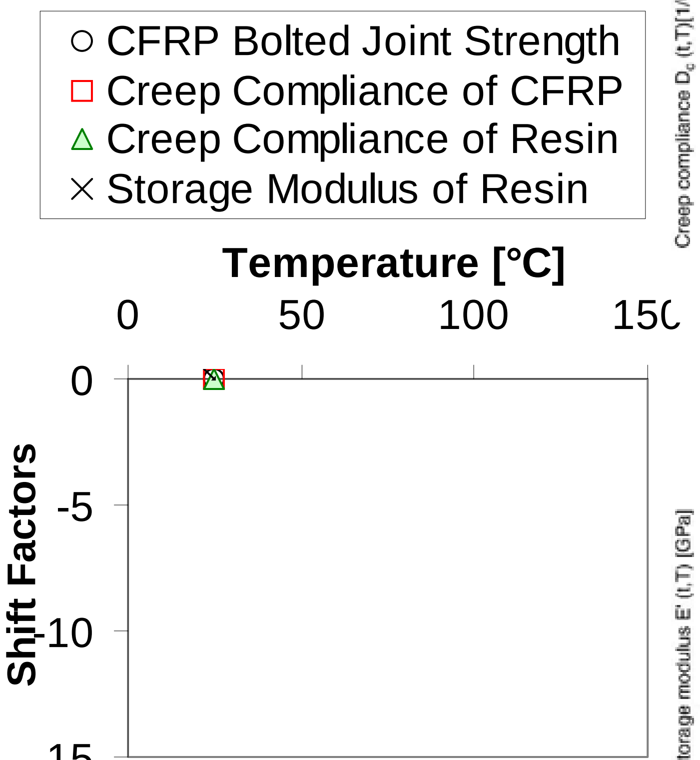
⇒ Accelerated evaluation of long term performance

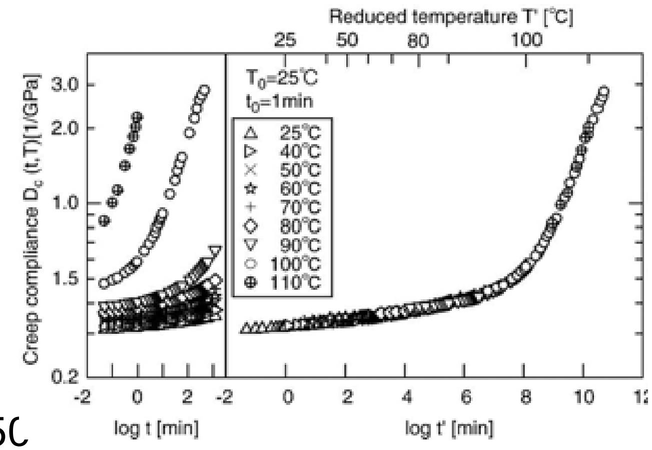


Time-Temperature Shift Factors

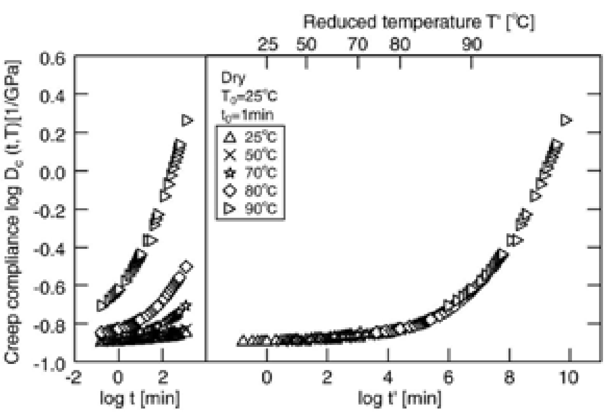


CFRP Bolted Joint Strength

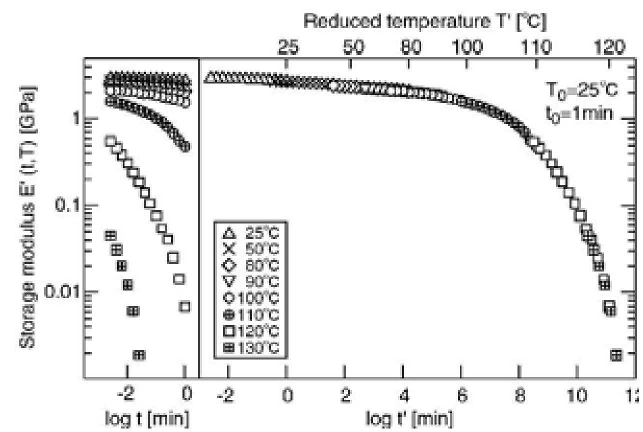




Creep Compliance of Resin



Creep Compliance of CFRP



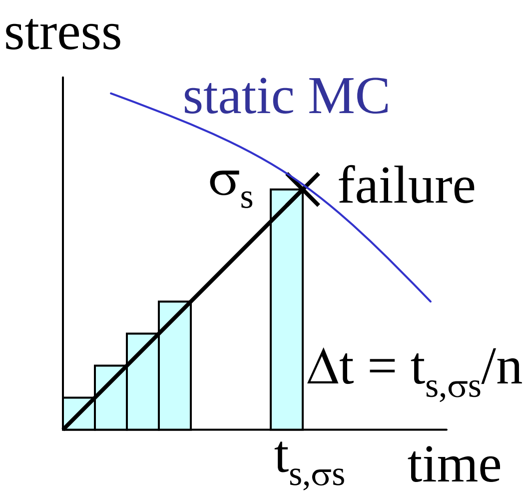
Storage Modulus of Resin

Same shift factors for various cases with common resin system

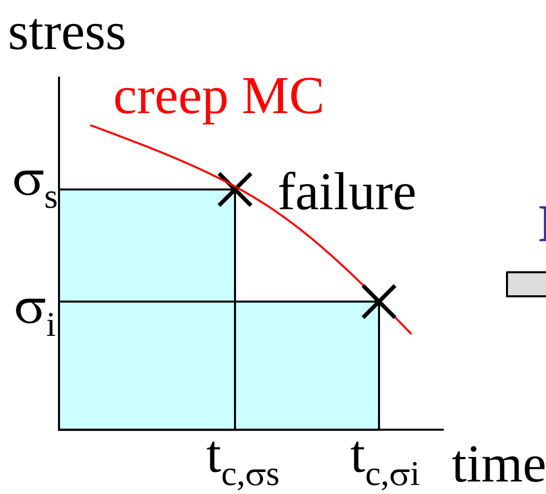
Creep Life Prediction

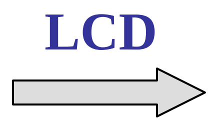
Linear Cumulative Damage Law (LCD) relates static and creep failures

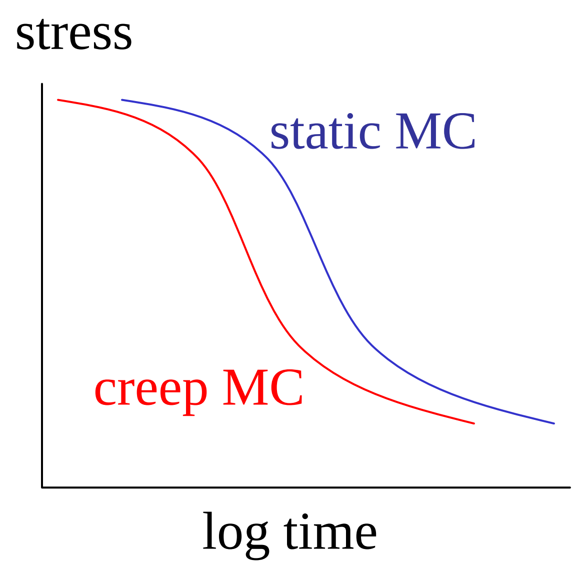
Static loading



Creep loading







Static (constant strain rate) loading considered as series of creep loads with increasing stress level.

Using LCD,

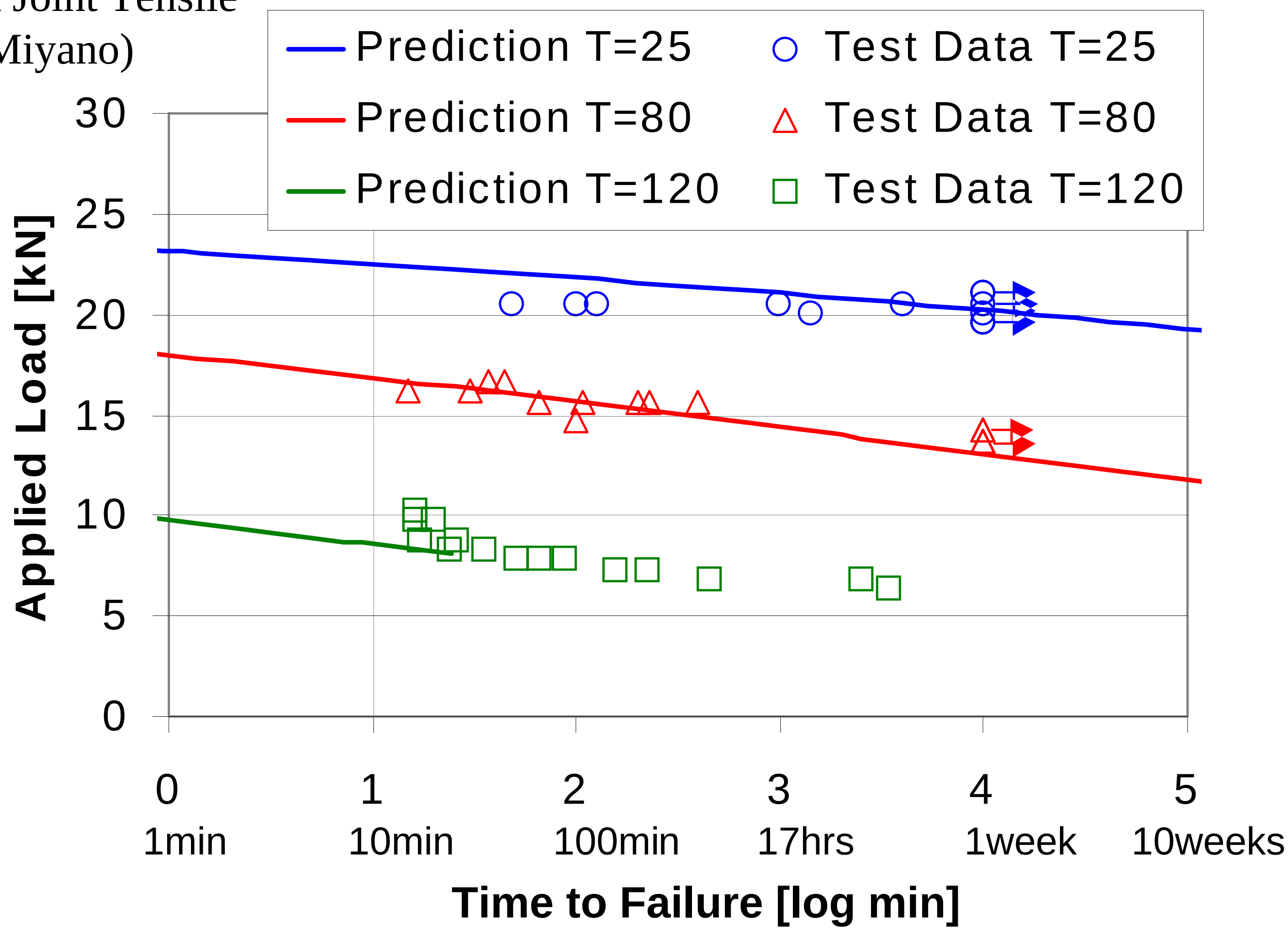
$$\frac{\Delta t}{t_{c,\sigma 1}} + \frac{\Delta t}{t_{c,\sigma 2}} + \frac{\Delta t}{t_{c,\sigma 3}} + \frac{\Delta t}{t_{c,\sigma 4}} + \ldots = 1 \Longrightarrow$$

creep life at σ

$$t_{c,\sigma} = f\,(t_{s,\sigma})$$

Creep Life Predictions and Measurements

CFRP Bolted Joint Tensile Creep Test (Miyano)



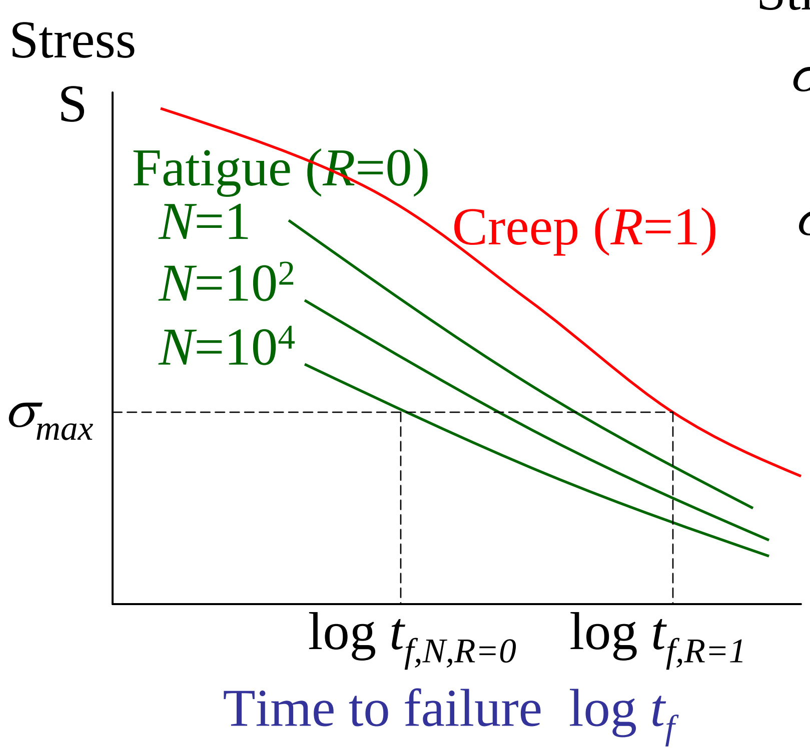
Creep life predictions agree with the creep test measurements

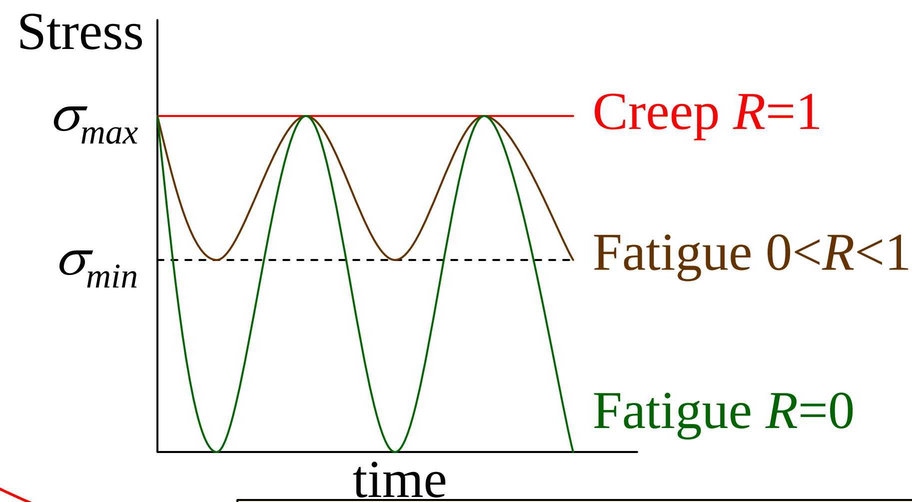
Fatigue / Creep Life Prediction

Creep and fatigue are related when rate dependence is considered

This allows

- Linear interpolation for arbitrary stress ratio ($R=\sigma_{min}/\sigma_{max}$)
- Life prediction for combination of creep and fatigue loads using LCD



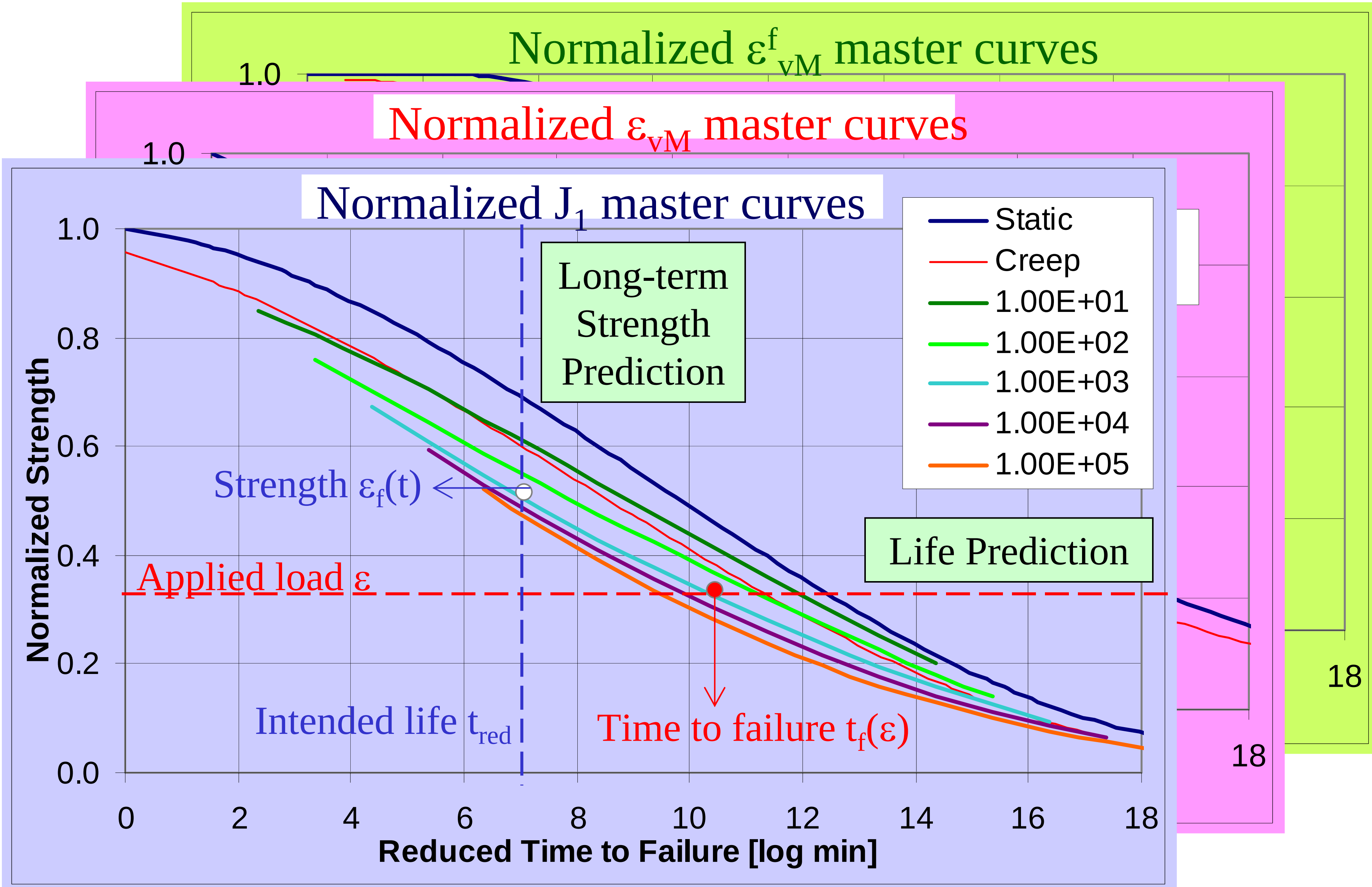


At σ_{max}, R, and N

Predicted life is

$$t_{f,N,R}=R\times t_{f,R=1}+(1-R)\times t_{f,N,R=0}$$

Prediction based on Master Curves



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Fatigue / Creep Combined Load

Linear Cumulative Damage (LCD) = Miner's Rule

with respect to time

only if correct frequencies are used

$$\frac{t_1}{t_{f,1}} + \frac{t_2}{t_{f,2}} + \frac{t_3}{t_{f,3}} + \frac{t_4}{t_{f,4}} + \ldots = 1$$

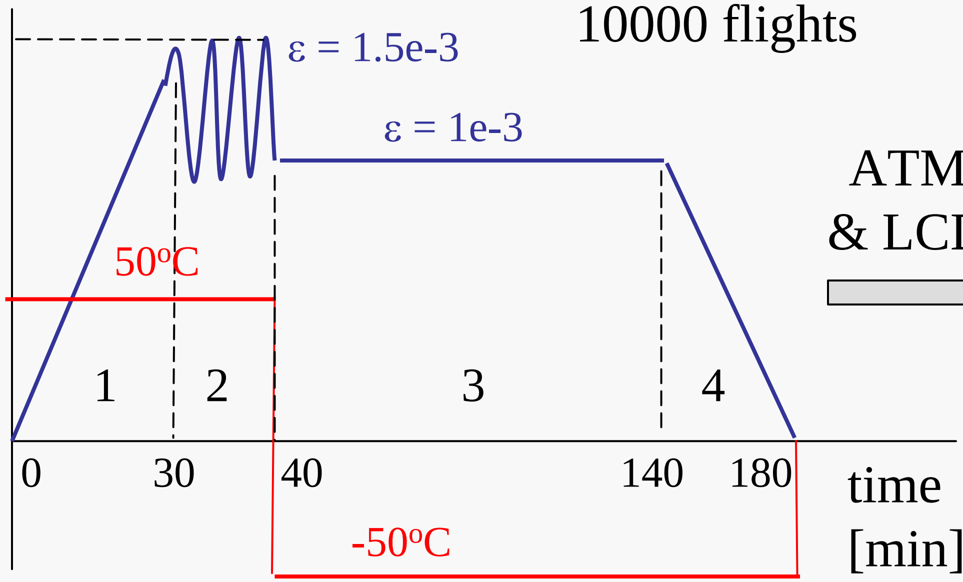
$\Rightarrow$ Require ATM

Example: Simplified flight load

Applied strain

Temperature

Repeated 10000 flights



ATM & LCD

i	t_i	$t_{f,i}$	Δ_i
1	$10^{5.5}$	$10^{6.4}$	0.11
2	$10^{5.0}$	$10^{5.2}$	0.57
3	$10^{6.0}$	10^{24}	0.00
4	$10^{5.6}$	10^{25}	0.00
sum			0.68

Life = 1/ 0.68 = 1.5

Residual Strength Prediction

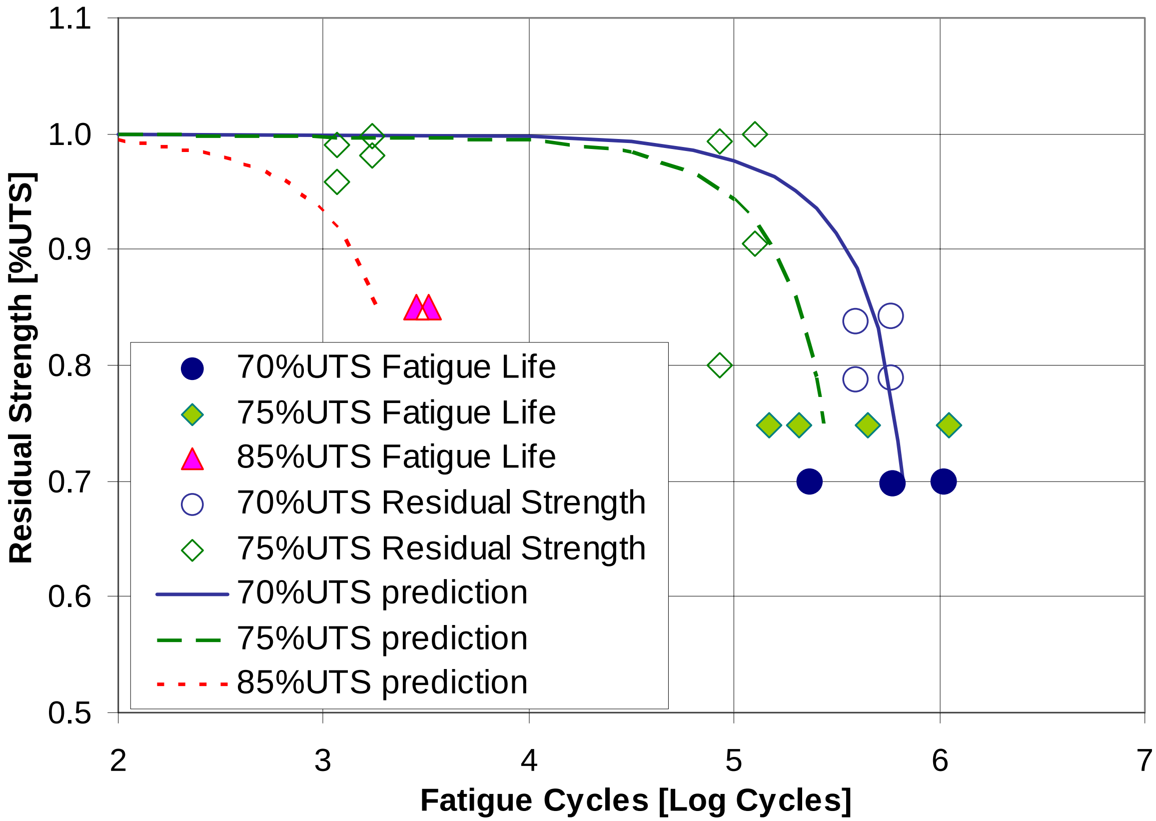
Linear Cumulative Damage (LCD)

$$\frac{t_1}{t_{f,1}} + \frac{t_2}{t_{f,2}} + \frac{t_3}{t_{f,3}} + \ldots = 1$$

After a damage of λ

$$\lambda + \frac{t_1}{t_{f,1}} + \frac{t_2}{t_{f,2}} + \frac{t_3}{t_{f,3}} + \ldots = 1$$

Residual strength at time to failure t_f = CSR strength at $t_f/(1-\lambda)$



Residual strength of graphite/epoxy laminate (test data from Verghese et al, 2001)

Effects of Moisture

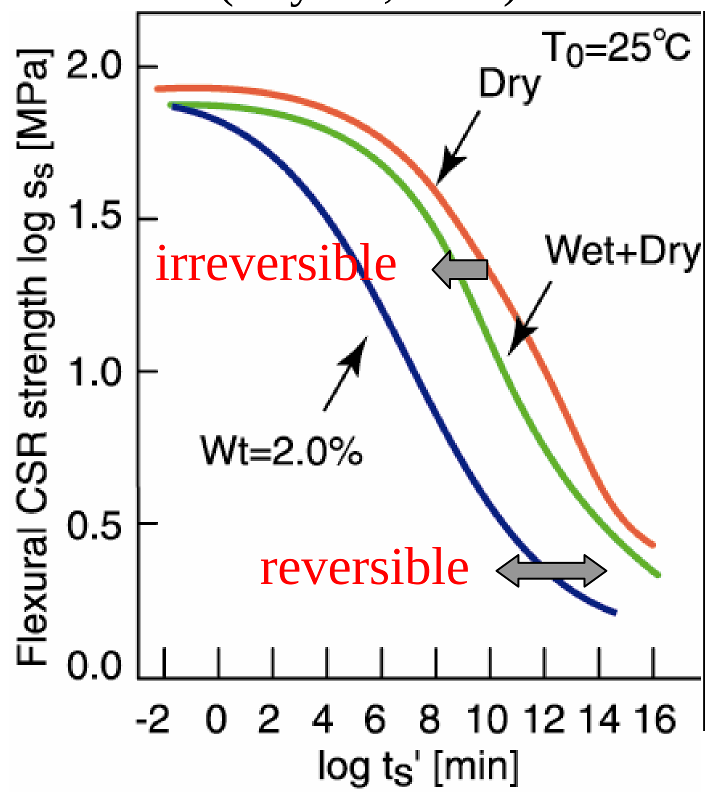
Reversible effects
- reduced modulus
- reduced strength
- lower T_g
- swelling of the resin

Temperature-Moisture Superposition
(2002, Miyano and Sekine)
$T_{eff} = T + a_M M$, where a_M = Moisture shift factor

Irreversible effects
- fiber/matrix interface failure
- ...

Micromechanics analysis of interface failure

CFRP [0] flexural strength
(Miyano, 2001)



Load Independent Degradation

Separate the long-term degradation to

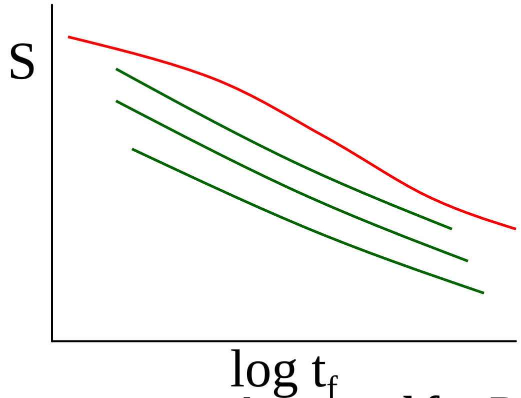
Load-dependent degradation
- Creep/fatigue failures
- Due to applied or hygro-thermally induced stress

→ **ATM**: Systematic prediction of load-dependent degradation

Load-independent degradation
- Assume no effect of applied loads
- Chemical degradation due to oxidization, UV, etc.

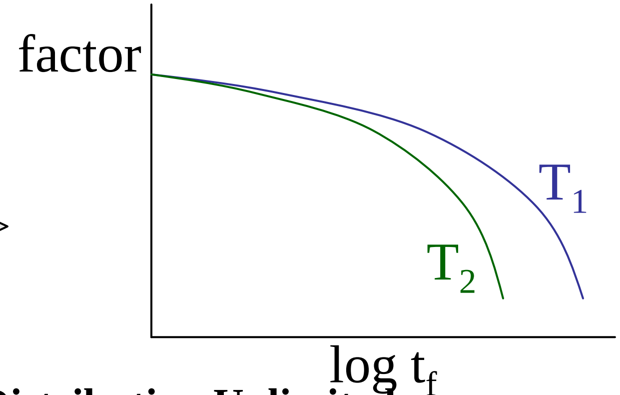
→ **Aging Tests**: Simplified tests without mechanical load

Master curves from ATM



combine

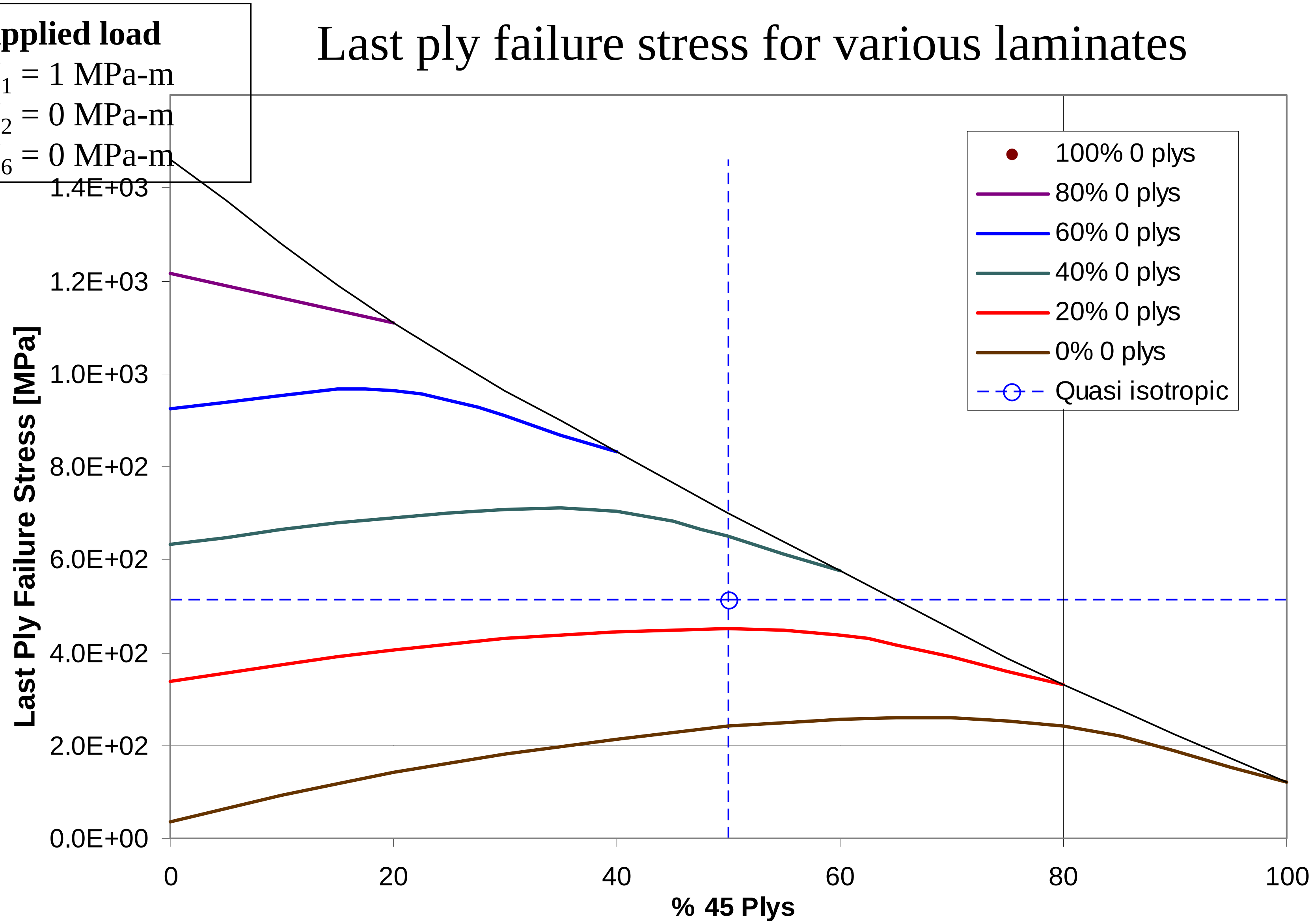
Degradation factors from aging tests (Thermal stability models by Boeing)



Contents

Conventional Carpet Plot

Applied load
N_1 = 1 MPa-m
N_2 = 0 MPa-m
N_6 = 0 MPa-m



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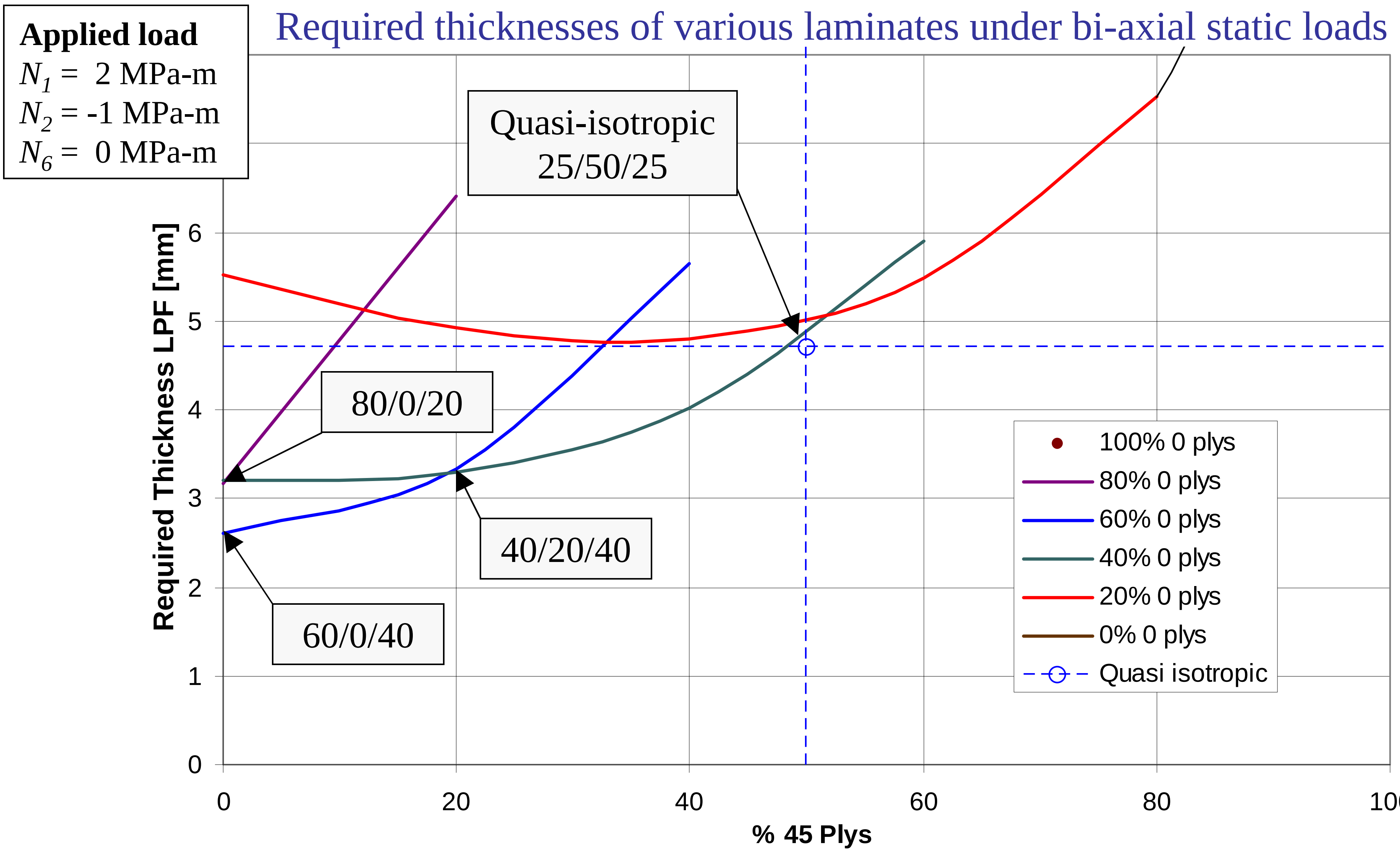
Electronic Carpet Plot Output



Up to 50% reduction in required thickness using wide ranges of ply orientations

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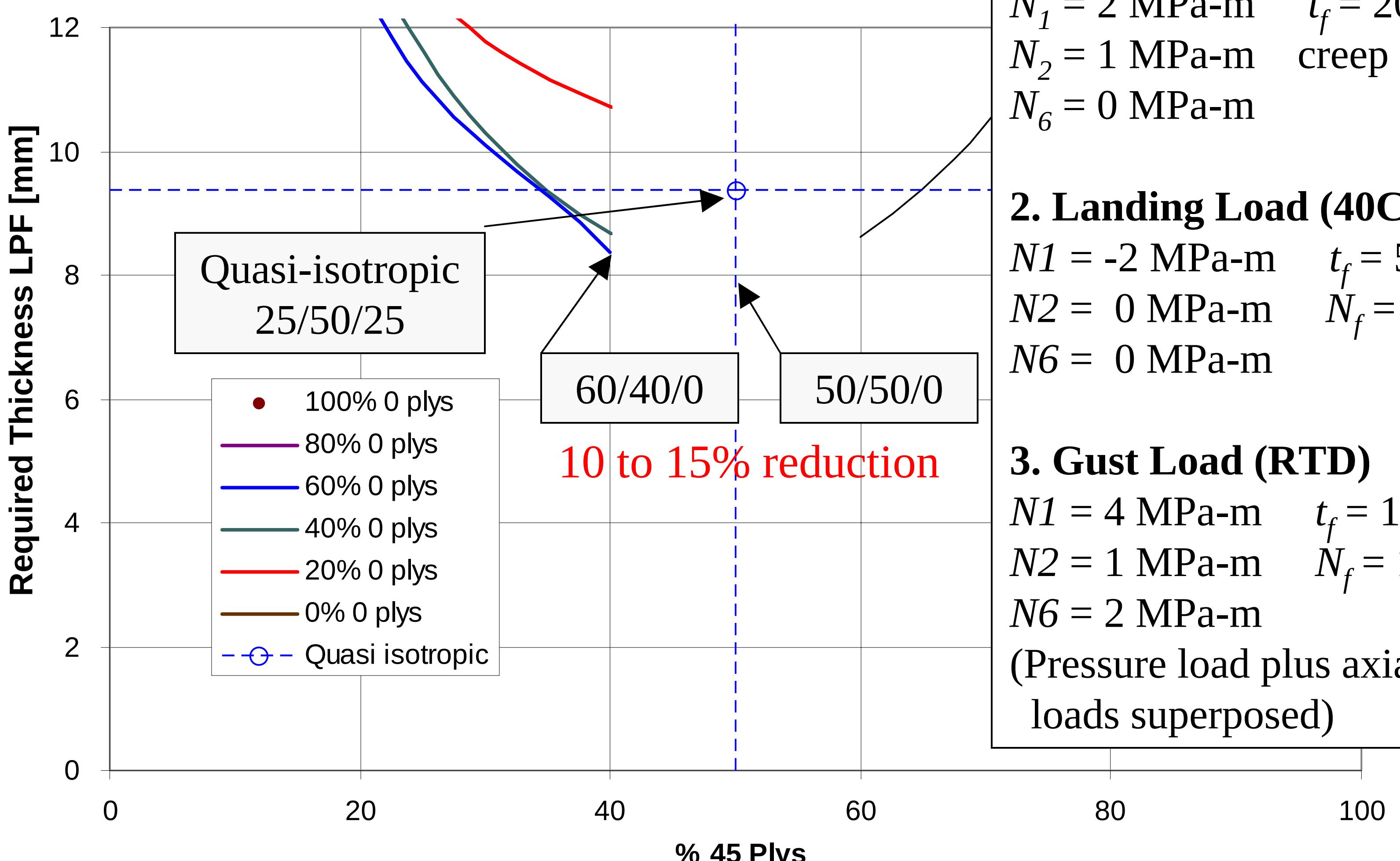
Electronic Carpet Plot – Multiple Loads

Required thicknesses of various laminates under multiple fatigue/creep loads



1. Pressure Load (RTD)

N_1 = 2 MPa-m t_f = 20 years

N_2 = 1 MPa-m creep load

N_6 = 0 MPa-m

2. Landing Load (40C, 0.5%)

N1 = -2 MPa-m t_f = 50000 min

N2 = 0 MPa-m N_f = 50000 cycles

N6 = 0 MPa-m

3. Gust Load (RTD)

N1 = 4 MPa-m t_f = 100 min

N2 = 1 MPa-m N_f = 100 cycles

N6 = 2 MPa-m

(Pressure load plus axial and shear loads superposed)

Optimum layup for multiple loads are not obvious

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Parameter Study

Initial and final fatigue strength ratios of quasi-isotropic laminate for RTD (room temperature dry) to HTW (hot wet) conditions

Applied load

$N_1 = 2$ MPa-m

$N_2 = 1$ MPa-m

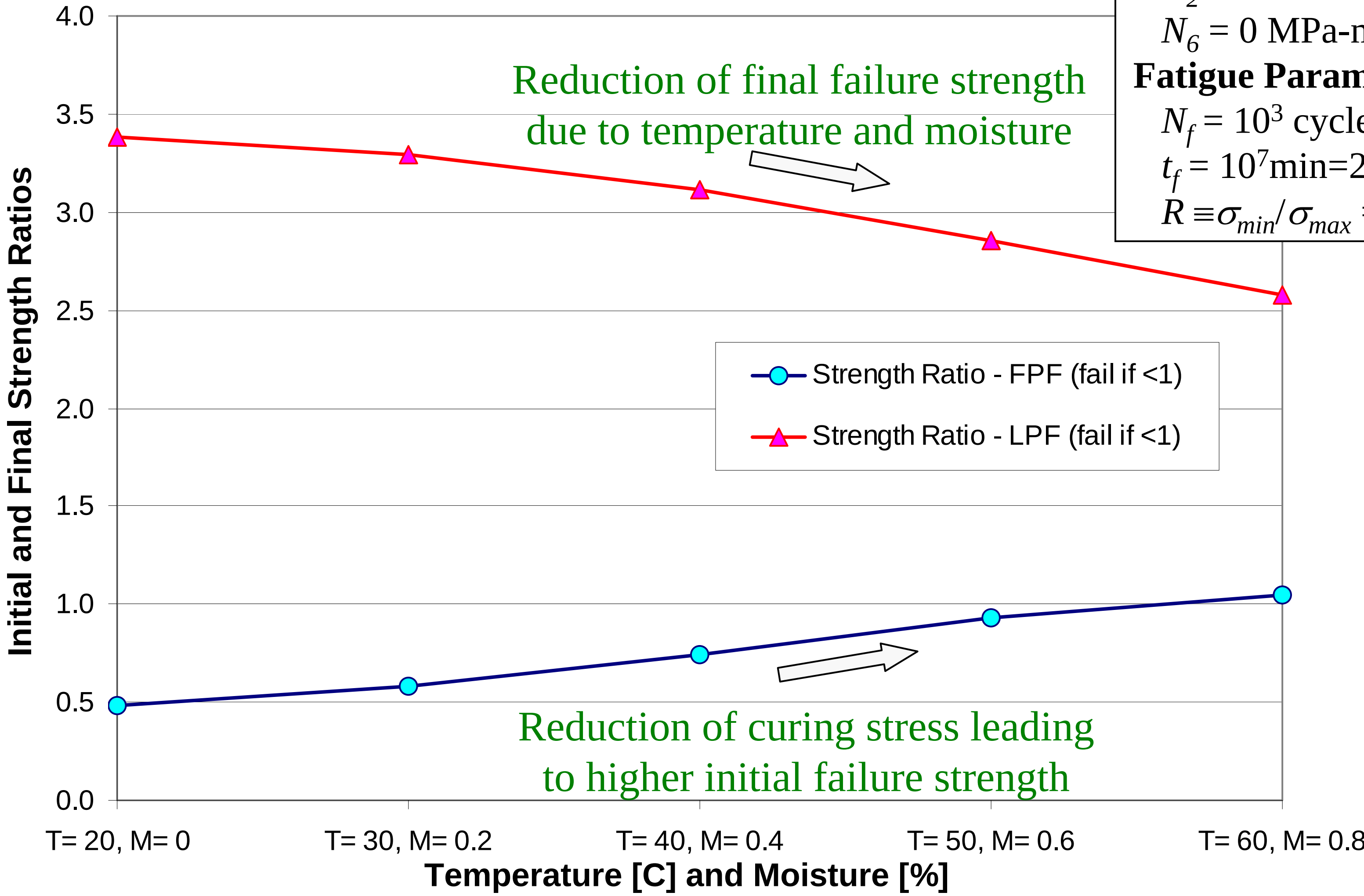
$N_6 = 0$ MPa-m

Fatigue Parameters

$N_f = 10^3$ cycles

$t_f = 10^7$min=20years

$R \equiv \sigma_{min}/\sigma_{max} = 0$



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Conclusions

Accelerated Testing Methodology (ATM) allows rapid generation of durability database as master curves.

Strain Invariant Failure Theory (SIFT) relates basic material durability database to the durability of composite laminates and structures

ATM/SIFT combination provides framework for evaluating the effects of various parameters associated with material selection, processing, design, loads, and environmental conditions.

Acknowledgements

AIM-C Program

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Durability Analysis Research

- Prof. Stephen W. Tsai and Prof. Richard M. Christensen of Stanford University
- Prof. Yasushi Miyano of Kanazawa Institute of Technology
- Prof. Sung Kyu Ha of Hanyang University